CYCLONE SOFTWARE User's guide

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FOREWORD

Cyclones are mostly used for removing industrials dust from air or process gases. They are the main type of gas-solid separator used because of their simple construction, low cost and ability to operate at high temperatures and pressures. Pollution and emission regulations have compelled designers to study the efficiency of cyclones. The software ‘Cyclone’ responds to this problem with a convivial interface, easy to use, furnishing a choice of four different models for predicting the cyclone performances and its geometry.

The original software 'Cyclone' was created through a collaborative work between Vincent Mathieu, Yann Le Moullec, Jean-Pierre Leclerc, Sabine Rode, Noël Midoux and Patrick Contal, members of the LRGP ('Laboratoire Réactions et Génie des Procédés') and Anthony Biget member of PROGEPI ('PROmotion du GEnie des Procédés dans l'Industrie'). The graphic part was conceived by Patrick Yax from the company SYSMATEC. The software runs on Windows.

This new version of the cyclone software represents a major update version of the software, and allows new functionalities as the using of an arrangement of several cyclones and the addition of a new resolution model for the using of a high loading complementary model. The graphical user interface has been entirely revised. All these new functionalities are presented in this document.

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NOMENCLATURE

a	[m]	: width of inlet cross-section
b	[m]	: height of inlet cross-section
c_i	[kg/m^3]	: concentration of particle in the region i
d_p	[m]	: particle diameter
g	[m/s^2]	: gravitational acceleration
h	[m]	: clearance between cyclone discharge opening and outlet gas pipe
h_{eq}	[m]	: equivalent height of the cyclone
f		: correction factor (depending on the type of pipe)
j_i	[kg/m^2.s]	: mass flux
m_w	[kg/s]	: re-entrained flow
n		: coefficient of the vortex
u	[m/s]	: tangential velocity
w_s	[m/s]	: sedimentation velocity
w_a	[m/s]	: axial velocity
w_e	[m/s]	: inlet velocity
w_i	[m/s]	: outlet velocity
w_r	[m/s]	: radial velocity
w_s	[m/s]	: terminal velocity
z		: axial co-ordonate

C_w		: drag coefficient
D		: angular momentum parameter
Dc	[m]	: cyclone diameter
De	[m]	: entrance diameter of the circular part
Di	[m]	: outlet diameter for the gas
Db	[m]	: outlet diameter at the bottom
D_{turb}	[m^2/s]	: coefficient of diffusivity
dc	[m]	: cut-size diameter
G		: factor describing the geometric configuration
H	[m]	: total height of the cyclone
L	[m]	: engagement length of cyclone
R	[m]	: radius
R_a	[m]	: outlet radius of cyclone
Rc*	[m]	: radius of the cylindrical part for the equivalent cyclone
R_e	[m]	: inlet radius of cyclone
R_i	[m]	: gas outlet pipe radius
Ri*	[m]	: equivalent radius of the engagement length of cyclone
Re		: Reynolds number
Se	[m^2]	: section of the cyclone inlet
Si	[m^2]	: section of the vortex finder inlet
T	[K]	: temperature
V_o	[m^3/s]	: inlet volumetric flow rate
V_s	[m^3/s]	: secondary volumetric flow rate

W	[N]	: flow resistance force
W	[N]	: centifugal force

α		: correction factor for contraction
δ	[m]	: thickness of the boundary layer
ε		: angle between the conical wall and the vertical
ξ_e	[Pa]	: pressure drop from the flow losses through the outlet pipe
ξ_i	[Pa]	: pressure drop from the inlet losses and friction losses
Δp	[Pa]	: pressure drop
λ		: friction factor
η	[m^2/s]	: kinematic viscosity
ϕ		: correction term for the profile of the boundary layer
ϕ_e	[kg/kg]	: inlet charge
ρ	[kg/m^3]	: gas density
ρ_p	[kg/m^3]	: solids density
τ	[s]	: relaxation time
μ	[Pa.s]	: dynamic viscosity

1. Background of cyclone design

1.1. Geometry of the cyclone

Cyclone can exist under different forms but the reverse flow cyclone represented in Figure 1 is the most common design used industrially. Two types of inlet are available: the axial and the tangential inlets shown in figure 2. The software runs on the case of reverse flow cyclone with a tangential rectangular inlet.
The principle of cyclone separation is simple: the gas-solid mixture enters on the top section tangentially. Then, the cylindrical body induces a spinning, vortexed flow pattern to the gas-dust mixture. Centrifugal force separates the dust from gas stream: the dust travels to the walls of the cylinder and down the conical section to the dust outlet and the gas exits through the vortex finder.

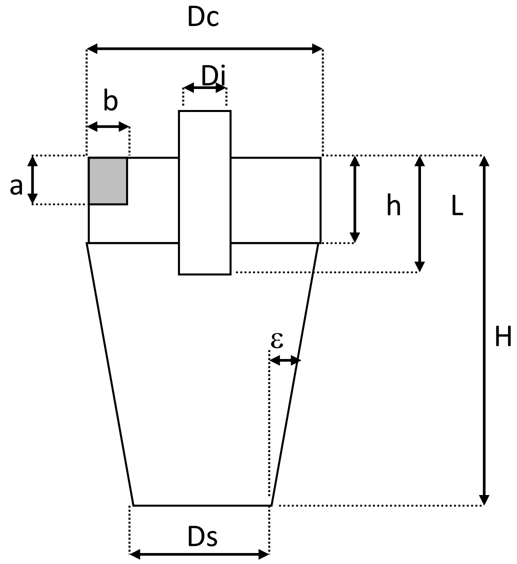


Figure 1 : Cyclone design configuration.

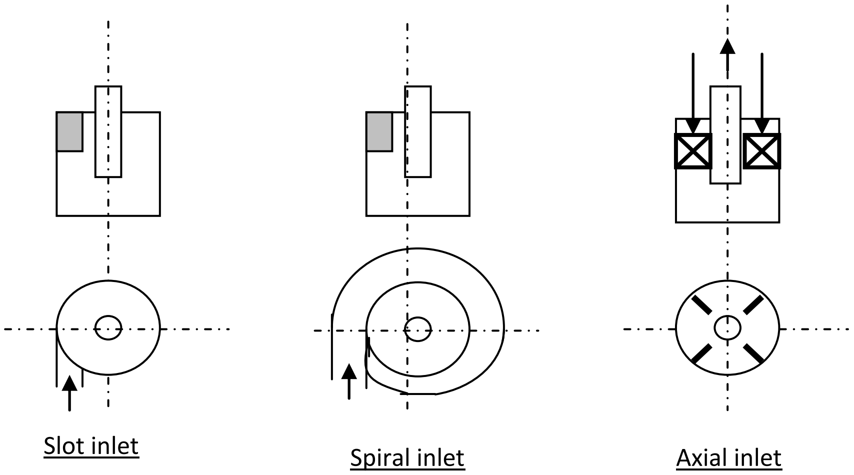


Figure 2: Type of inlet constructions.

1.2. Significant parameters of the cyclone

Several parameters enable to describe the cyclone:

∗ <u>Geometric shape</u>

Eight geometric parameters allows to describe the cyclone: a, b, Di, Ds, h, L, H, Dc as shown in Figure 1. However it is usual to characterize the reverse flow cyclone as the ratio of parameters normalized by the diameter Dc:
a/Dc, b/Dc, Di/Dc, Ds/Dc, h/Dc, L/Dc, H/Dc

∗ <u>Cut size</u>

The cut size is the particle diameter separated at 50%, so called “cut diameter”.

∗ <u>Efficiency</u>

Efficiency is the ratio between particle of diameter dp in the exit gas and in the feed.

2. Description of the software

Please make sure your computer works with point and not comma. Otherwise, change the configuration.

The software starts by a double click on Cyclone icon in the cyclone group. Once the application opens, the interface with a cyclone (Figure 3) appears.

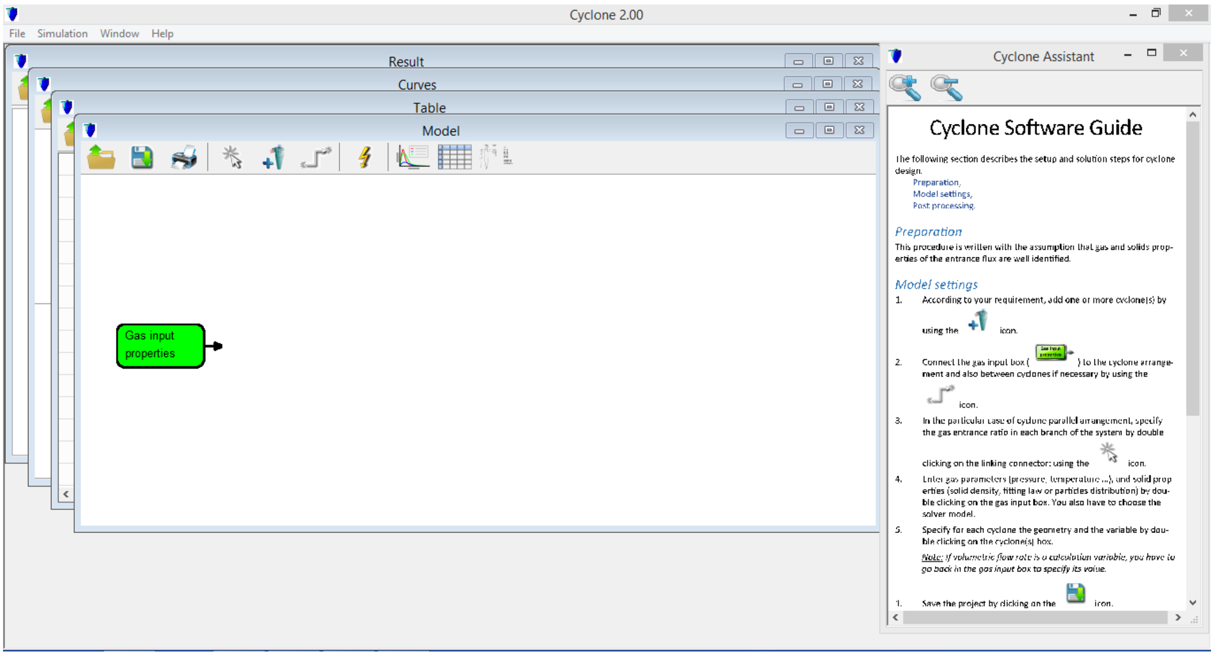


Figure 3: Graphic interface of the Cyclone Software.

2.1. Description of the menus

Four commands are available: File, Simulation, Window, Help.

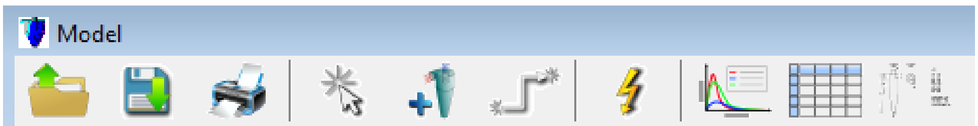
<u>File menu:</u>

In this menu, the user can do the following operations:

- [***new***]: Create a new file.
- [***open***]: Open a file.
- [***save***] and [***save as***]: The files are saved on the form 'filename.cyc'.
- [***print***] and [***print setup***]: Operation equivalent to 'print screen' which can be used to print the results.
- [***exit***]: Exit the software.

<u>Simulation menu:</u>

- [***Calculate***]: permits to launch the simulation. This command is also available on the icon in shape of a flash by a click of the mouse as shown as follow:



Icon for calculation

Menu Window:

This menu is separate in two parts. As described as follow, the first set of options allows to access to the chosen window.

- [***Model***]: is used for the design model parameters entrance.
- [***Curve***]: the curves result of the designed cyclone in term of efficiency, entrance, foot and head distribution are resumed in this windows.
- [***Table***]: the data series result of the designed cyclone in term of efficiency, entrance, foot and head distribution are resumed in this windows.
- [***Result***]: dimensions and mean information of the designed cyclone are resumed in this windows.

The other options available in this menu described as follow lead to different working reorganization of the windows described previously.

- [***Cascade***]: select this option button to arrange and size the windows so that they overlap one another with only their title bars showing.
- [***Title***]: select this option button to arrange and size the windows so that they all fit side by side on the screen in the same order you opened them.

Menu Help:

- [***Cyclone Assistant***]: commands the opening of an Assistant Windows which helps you and describes the setup and solution steps for the cyclone(s) design.
- [***Help***]: commands the opening of the present document.
- [***About cyclone***]: commands a window where the references of the programmers of PROGEPI and SYSMATEC are reported.

2.2. Choice of the cyclone(s) configuration - Schematic representation of the system

A major innovation of this software release is the possibility to use one or more cyclones to design/optimize your installations. In each configuration case, through the model window which is accessible with the "menu Window" or through the icon  , the user has to build an association of one or more cyclones that are interconnected to form a network having only one inlet.

The different possibilities and combinations offered to the user can be summarize in two configurations and are described as follow.

2.2.1. Only one cyclone is use for the installation design.

When the user needs to use only one cyclone, as described in Figure 4, he has to create a network with a cyclone and a connector which links the inlet gas input to the entered cyclone.

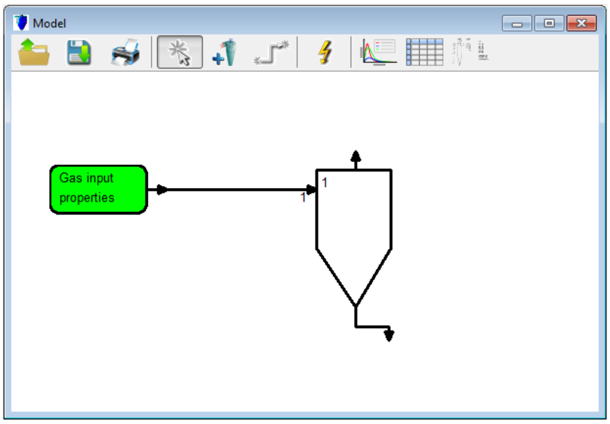


Figure 4: Design installation using only one cyclone.

As described as follow to successfully solve the system, the user needs to fill some informations as the gas and particles properties or several cyclone characteristics...
These informations are accessible by double clicking on the gas input and the cyclone diagrams. These steps will be explained further down in this document.

2.2.2. At least two cyclones are used for the installation design.

In the particular case where the user needs to design an installation which contains more than one cyclone, the software offers the possibilities to develop a complex network consisting on an arrangement of series and / or parallel cyclones configurations. The Figure 5 shows an example of a complex network using a series and parallel cyclones arrangement.

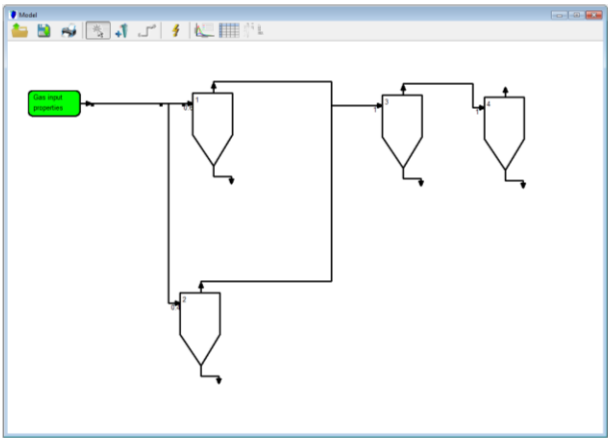


Figure 5: Example of a complex network which uses a combination of many cyclones.

<u>Limitations of the model</u>

However this model has some limitations:

- When the user chooses to use a parallel combination of at least two cyclones, in order to respect the mass flow rate balance in the whole network, the user has to specify the flow rate ratio in each connector by double clicking on it.
- The number of cyclones which can be used is limited to a maximum number of ten cyclones.

- As described in each cyclone characteristics, the volumetric flow rate in each cyclone will be calculated based on the global flow rate which can be filled in the gas input panel and the flow distribution in the connectors. The user has to define the total volumetric gas flow rate in the gas input diagram. This quantity will be used as a variable to solve the system.

2.3. Choice of the parameters

The running conditions have to be filled in the window ‘Parameters’, before the calculation. Six types of information are required:

- the gas characteristics,
- the solid characteristics,
- the model chosen for the calculation,
- the geometry,
- the variables,
- the values of d_p for eventual calculation of separation efficiency.

2.3.3. **The gas characteristics**

Two cases are possible to define the gas characteristics. These informations are available by double clicking on the [***Gas input parameters***] diagram and are presented here:

⇒ **The gas used is air**

First click on the [***Gas input parameters***→***Gas***] tab, then fill in the pressure and the temperature data for the running conditions studied. No use to enter the density and the viscosity: they are automatically calculated by the software in function of the temperature and the pressure, as described in Figure 6. After simulation, their values appear on the [***Gas input parameters***] window.

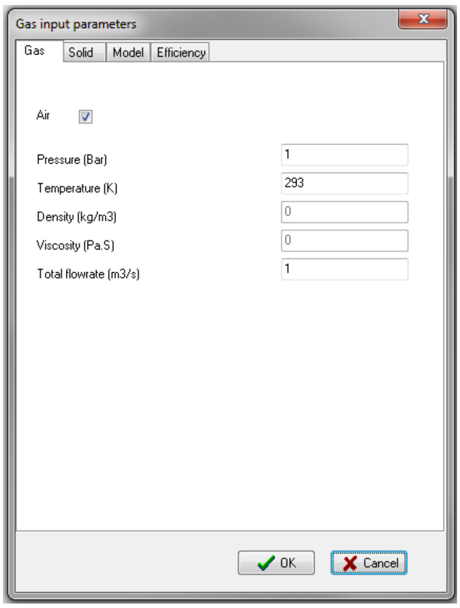


Figure 6: Example of gas choice ‘Air’ in the window ‘Parameters’

Procedure of calculation for density:
An equation of Van Der Waals [10] with one term is used for evaluating the density. This relation gives very good approximations (error <10%) of the real values for pressure inferior to 100 bar and for temperature up to 1300 K. However the user can choose to enter its own values if the precise values are known or out of the previous limits described: de-clicked the case 'Air' and enter by yourself the values.

Procedure of calculation for viscosity:
A viscosity relation for a rigid, non-interacting sphere model at low pressure is used [11]. In order to evaluate viscosity for all pressure, the Reichenberg method is used to complete the first model [11]. This relation shows also very good agreement with real values (error < 5%). In this case too, if the user prefers entering its own values, he can de-click the case 'Air' and enter them directly in the window.

⇒ **The gas used is not air**

In this case, the user has to enter the four parameters characterizing the gas: pressure, temperature, viscosity and density. Figure 7 gives an example of this case.

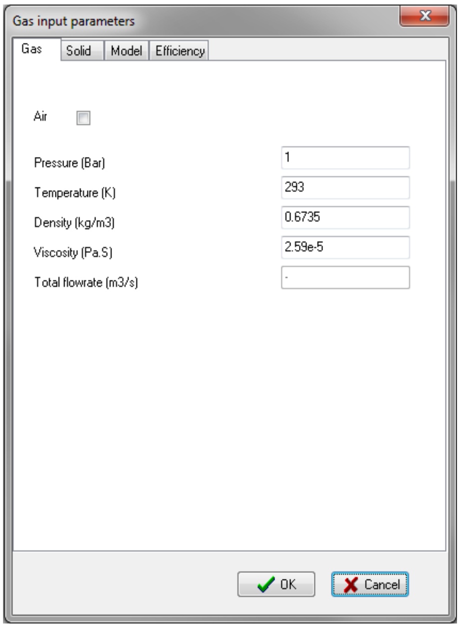


Figure 7: Example of 'non-Air' choice for the gas

Note:
The *'Total flow rate'* of the gas at the system entrance is accessible only if the volumetric flow rate was previously defined as a calculation variable in the cyclone characteristics. Therefore this expression is automatically activated if the user chooses to use at least two cyclones.

2.3.4. The solid characteristics

As described in Figure 8, the user firstly has to fill in the [***Gas input parameters***→S***olid***] tab the solid density and the solid concentration of particles of the studied system entrance.

Additionally to the solid density, the solid distribution has to be known in order to obtain a good evaluation of the researched parameters. Two cases are also possible:

⇒ **The distribution is known experimentally**

The user knows a size distribution: this is the case of a discontinuous distribution. Choose in the menu [***Fitting law at entrance***] the case [***User***]. A table appears where the user can write the particle diameter and the inferior cumulate frequency. Figure 8 shows an example of distribution.

<u>BEWARE:</u>

Data on the table have to be filled according to some rules:

- The first couple of data must be of the type (d_i, 0).
- The last couple of data must be of the type (d_i, 1).
- The couples of data must be entered in an increasing order.

The software 'Cyclone' will find directly the best fitting law (Rosin-Rammler or Normal-log law) for the data of the table among the two recorded laws.

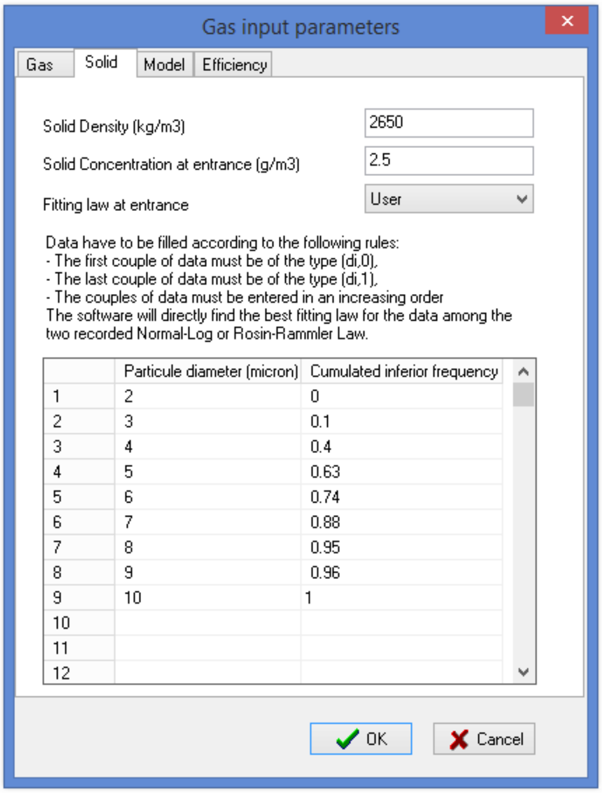


Figure 8: Example of Distribution type 'User'

⇒ **The distribution is unknown**

According to literature [9], there are two fitting laws that are well adapted to describe a size distribution: the Normal-Log law and Rosin-Rammler law. Both are accessible by the definition of only two parameters:

- The Rosin Rammler law: characterized by n (dispersion index) and d_m(average diameter of Rosin Rammler).

- The Normal-Log law: characterized by μ (first order moment) and σ (second order moment).

Default values are entered in the software and can be kept, as a good approximation, by the user when he does not have an idea of the parameter values.

2.3.5. The calculation model

As shown in the Figure 9, five different models are available in the software via the [***Gas input parameters***→***Model***] tab.

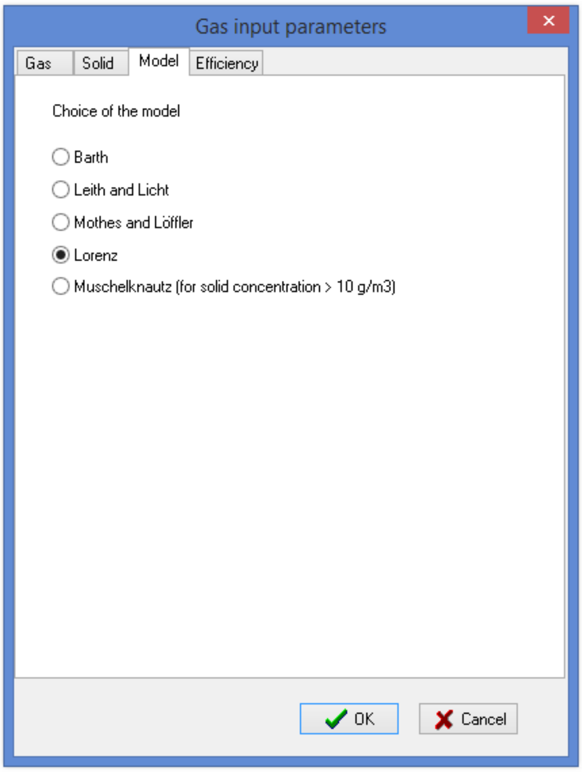


Figure 9: Choice of the calculation models available for calculation.

Their calculation principles are described in details in section 3. Table 1 shows the type of results obtained with the five models. In order to guide the user for choosing the best model, section 4 gives advice made on the studies of different works done on cyclone.

Table 1: Type of results obtained with the four models.

	Barth	Leicht & Licht	Mothes & Löffler	Lorenz	Muschelknautz
Geometry	✓	✓	✓	✓	✓
Cut-size	✓	✓	✓	✓	✓
Pressure drop	✓	✓	✓	✓	✓
Efficiency	✘	✓	✓	✓	✓

2.3.6. The geometry

Figure 10 shows the presentation of the [***Cyclone→Geometry***] tab. Two cases are possible:

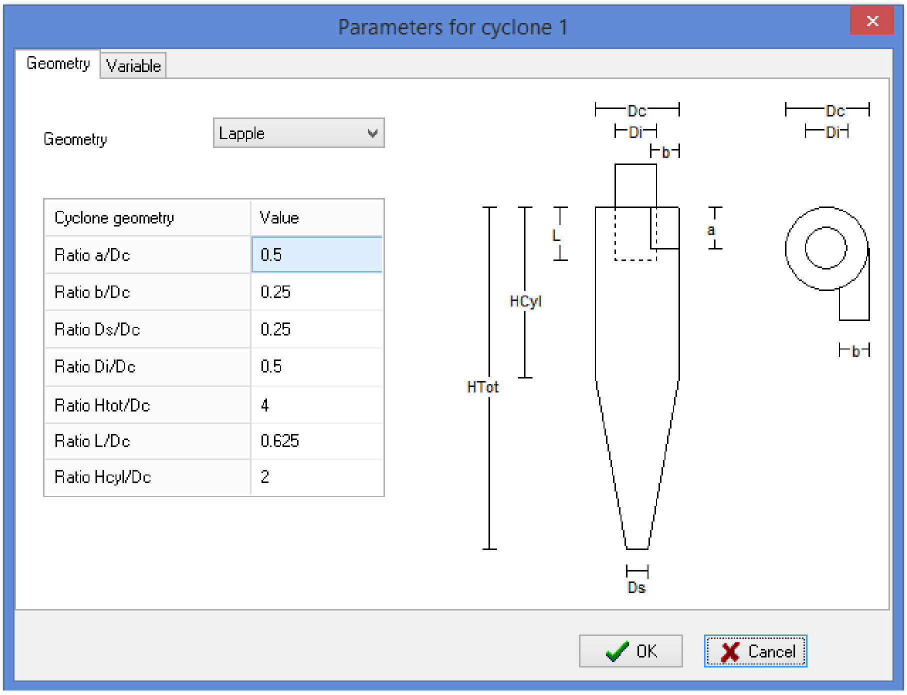


Figure 10: Example of choice for the chose cyclone geometry

⇒ **The cyclone geometry is already known:**

Choose the case [***Geometry→User***] where ratios can be entered. The notations are those described on the cyclone Figure 1.

⇒ **The cyclone geometry is unknown:**

The software gives the choice of defined configurations used by conceivers of models. These classical geometries of cyclone have been reported in Table 2. The high interest is that once the configuration is chosen, there is just one parameter (Dc) to evaluate to obtain the all cyclone dimensions.

Table 2: Geometric ratios for 8 models.

	a/Dc	b/Dc	Ds/Dc	Di/Dc	H/Dc	L/Dc	h/Dc
LAPPLE	0.5	0.25	0.25	0.5	4	0.625	2
SWIFT1	0.5	0.25	0.4	0.5	3.75	0.6	1.75
SWIFT2	0.44	0.21	0.4	0.4	3.9	0.5	1.4
STAIRMAND	0.5	0.2	0.375	0.5	4	0.5	1.5
PETERSON and WHITBY	0.583	0.208	0.5	0.5	3.173	0.583	1.333
LORENZ1	0.533	0.133	0.333	0.333	2.58	0.733	0.693
LORENZ2	0.533	0.133	0.333	0.233	2.58	0.733	0.693
LORENZ3	0.4	0.1	0.333	0.233	2.58	0.733	0.693

2.3.7. The variables

To run the software, the user needs to enter at least two variables. One can choose in the [***Geometry→Variable***] tab which couple or triplet he wants to enter.
The different combinations available are:

- Volumetric flow rate & Cyclone diameter
- Cyclone efficiency & Cyclone diameter
- Cut diameter & Cyclone diameter
- Pressure drop & Cyclone diameter
- Cyclone efficiency & Volumetric flow rate
- Cut diameter & Volumetric flow rate
- Pressure drop & Volumetric flow rate
- Pressure drop & Volumetric flow rate & Cyclone efficiency
- Pressure drop & Volumetric flow rate & Cut diameter

Each of these configurations enables to launch the optimization of the parameters and is available when the user chooses to use only one cyclone for the design of its system. In the particular case where the user chooses to use at least two cyclones, some combinations are not available. The user can choose only the combinations where the volumetric flow rate appears. These possibilities are resumed in Table 3.

Table 3: Restriction of the model in terms of available combinations.

Number of cyclone(s) used	**1**	**2 - 10**
Volumetric flow rate & Cyclone diameter	✓	✓
Cyclone efficiency & Cyclone diameter	✓	✘
Cut diameter & Cyclone diameter	✓	✘
Pressure drop & Cyclone diameter	✓	✘
Cyclone efficiency & Volumetric flow rate	✓	✓
Cut diameter & Volumetric flow rate	✓	✓
Pressure drop & Volumetric flow rate	✓	✓
Pressure drop & Volumetric flow rate & Cyclone efficiency	✓	✓
Pressure drop & Volumetric flow rate & Cut diameter	✓	✓

2.3.8. The efficiency

This menu is available for all the models except for Barth model. The user can enter the particle diameter values for which he wants to know the separation efficiencies, in the [***Gas input parameters→Efficiency***] tab. Once all the parameters are filled in and the software

runs, the values of the corresponding efficiencies appear in the different columns of the table. Efficiencies are given in fraction from 0 to 1. Figure 11 presents the window 'Efficiency' after calculation.

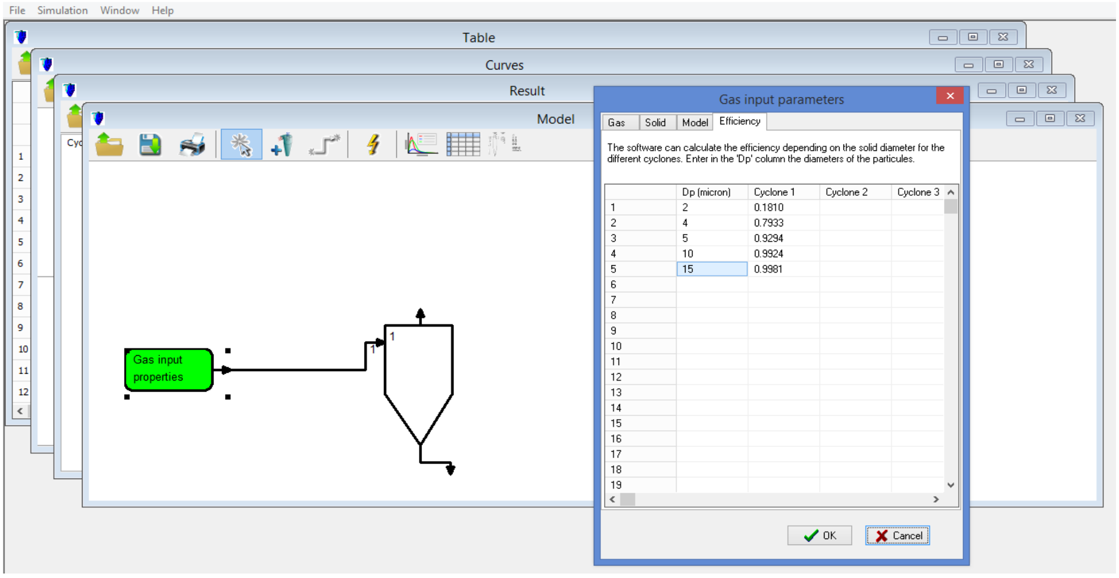


Figure 11: Efficiency results of particular particle size.

2.4. Visualization of results

After calculation, some results appear directly in window of the interface: geometry, cut-size, pressure drop, efficiency and volumetric flow rate. Figure 10 shows typical results.

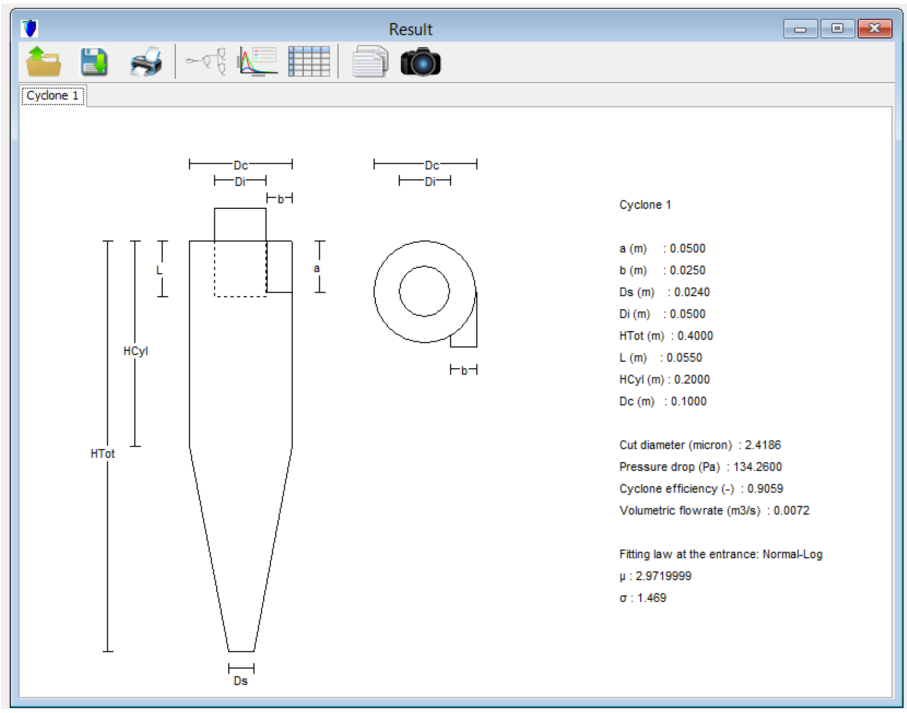


Figure 12: Example of data results window.

If at least two cyclones were used, the results of each cyclone can be consulted in different tab as shown in Figure 13.

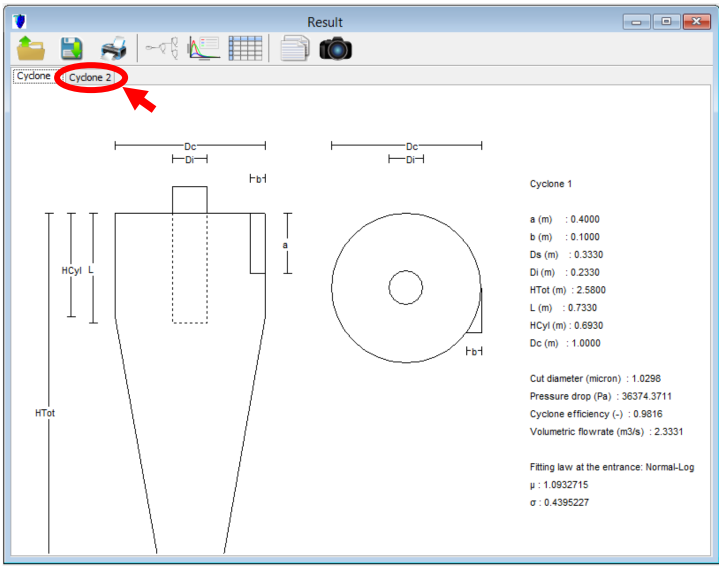
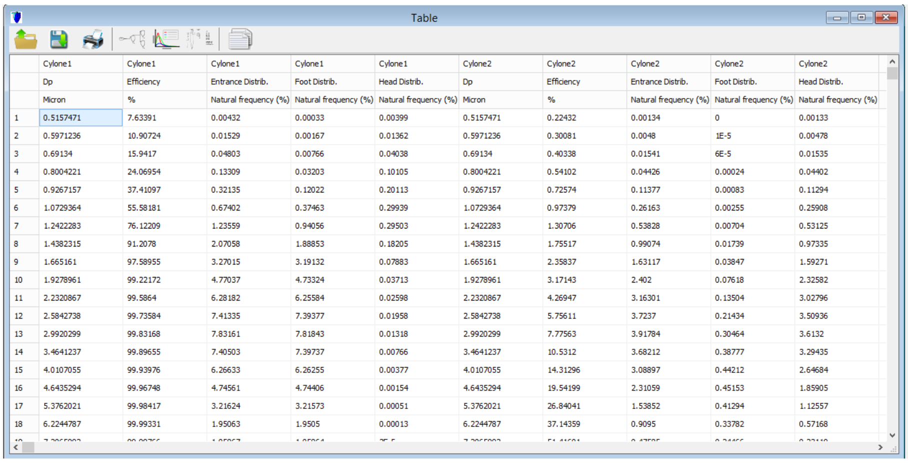


Figure 13: Results visualization for an arrangement of several cyclones.

As shown in Figure 14 and Figure 15, the separation efficiency and the particles distribution at the entrance, collected at the foot or extracted at the head of each cyclone can be visualized and exploited via the [***Table***] and [***Curves***] result windows.



	Cylone1	Cylone1	Cylone1	Cylone1	Cylone1	Cylone2	Cylone2	Cylone2	Cylone2	Cylone2
	Dp	Efficiency	Entrance Distrib.	Foot Distrib.	Head Distrib.	Dp	Efficiency	Entrance Distrib.	Foot Distrib.	Head Distrib.
	Micron	%	Natural frequency (%)	Natural frequency (%)	Natural frequency (%)	Micron	%	Natural frequency (%)	Natural frequency (%)	Natural frequency (%)
1	0.5157471	7.63391	0.00432	0.00033	0.00399	0.5157471	0.22432	0.00134	0	0.00133
2	0.5971236	10.90724	0.01529	0.00167	0.01362	0.5971236	0.30081	0.0048	1E-5	0.00478
3	0.69134	15.9417	0.04803	0.00766	0.04038	0.69134	0.40338	0.01541	6E-5	0.01535
4	0.8004221	24.06954	0.13309	0.03203	0.10105	0.8004221	0.54102	0.04426	0.00024	0.04402
5	0.9267157	37.41097	0.32135	0.12022	0.20113	0.9267157	0.72574	0.11377	0.00083	0.11294
6	1.0729364	55.58181	0.67402	0.37463	0.29939	1.0729364	0.97379	0.26163	0.00255	0.25908
7	1.2422283	76.12209	1.23559	0.94056	0.29503	1.2422283	1.30706	0.53828	0.00704	0.53125
8	1.4382315	91.2078	2.07058	1.88853	0.18205	1.4382315	1.75517	0.99074	0.01739	0.97335
9	1.665161	97.58955	3.27015	3.19132	0.07883	1.665161	2.35837	1.63117	0.03847	1.59271
10	1.9278961	99.22172	4.77037	4.73324	0.03713	1.9278961	3.17143	2.402	0.07618	2.32582
11	2.2320867	99.5864	6.28182	6.25584	0.02598	2.2320867	4.26947	3.16301	0.13504	3.02796
12	2.5842738	99.73584	7.41335	7.39377	0.01958	2.5842738	5.75611	3.7237	0.21434	3.50936
13	2.9920299	99.83168	7.83161	7.81843	0.01318	2.9920299	7.77563	3.91784	0.30464	3.6132
14	3.4641237	99.89655	7.40503	7.39737	0.00766	3.4641237	10.5312	3.68212	0.38777	3.29435
15	4.0107055	99.93976	6.26633	6.26255	0.00377	4.0107055	14.31296	3.08897	0.44212	2.64684
16	4.6435294	99.96748	4.74561	4.74406	0.00154	4.6435294	19.54199	2.31059	0.45153	1.85905
17	5.3762021	99.98417	3.21624	3.21573	0.00051	5.3762021	26.84041	1.53852	0.41294	1.12557
18	6.2244787	99.99331	1.95063	1.9505	0.00013	6.2244787	37.14359	0.9095	0.33782	0.57168

Figure 14: Table window which resume all efficiency and distribution results.

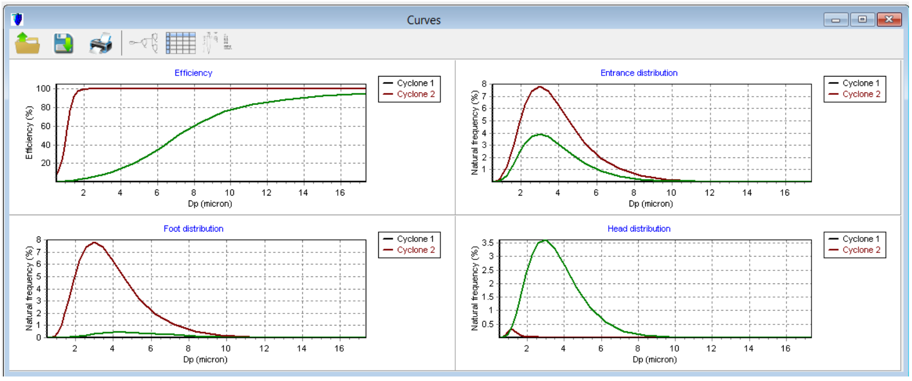


Figure 15: Curves window which resume all efficiency and distribution results.

Note: As shown in Figure 16, the user has the possibility to modify the axis range of all graphs by double-clicking on abscissa or ordinate axis.

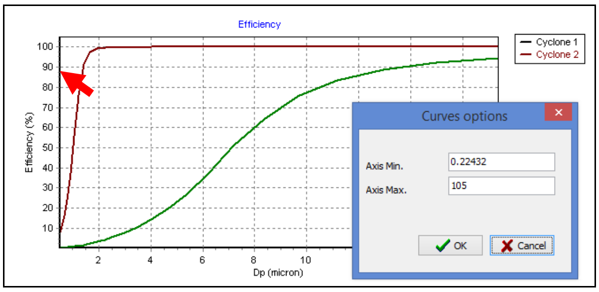
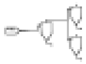


Figure 16: Axis range modification.

Results can be exported by double clicking on both  and  icons or using cut/copy and paste functions. The model settings can be consulted or modified at any time by clicking on the  icon.

2.5. Error messages

The window [Parameters] is saved once all the parameters are properly entered. In the case of no respect of the conditions described previously, a message of error will appear. Table 3 next page describes the different type of errors, the message of error and the corrections to do, to make the software run.

3. Description of the used models

Since the first application of aerocyclones in 1886, several models have been developed for the calculation of the design parameter, pressure drop and efficiency. The software 'Cyclone' uses four of them:

- Barth model [2]
- Leith and Licht model [3,4]
- Möthes and Löffler [5]
- Lorenz model [8]
- Muschelknautz (for solid concentration > 10 g/m^3) [9,10,11,12,13,14,15]

The following part presents some of the elements used to conceive the model. Due to the complexity of the different procedures, the description of the conception of these models are not complete. The aim is to inform the user of the considered hypothesis and the principle of calculation of the model.

3.1. First considerations

Some hypothesis are common to all these models:

- Particles are spherical
- Particle motion is not influenced by the presence of neighboring particles
- Radial velocity of the gas equals zero
- Radial force on the particle is given by Stokes's law

3.2. Barth model

Barth [2] proposed a simple model based on a force balance. This model enables to obtain the cut-size and the pressure drop values. The principle of calculation consists on the fact that a particle carried by the vortex endures the influence of two forces: a centrifugal force Z and a flow resistance W. They are expressed at the outlet radius R_i where the highest tangential velocity occurs:

$$W = C_w \frac{\pi}{4} d_p^2 \frac{\rho}{2} w_r^2 \tag{1}$$

$$Z = \frac{\pi}{6} d_p^3 (\rho_p - \rho) \frac{u_2}{R_i} \tag{2}$$

$$C_w = \frac{24}{\mathrm{Re}_p} = \frac{24\mu}{d_p.w_r(R_i).\rho} \tag{3}$$

The tangential velocity at Ri equals:

$$w_r(Ri) = \frac{\dot{V}_0}{2\pi.Ri.(H-L)} \tag{4}$$

The radial velocity u(Ri) equals:

$$u(Ri) = \frac{\dot{V}_0 / \pi.Ri^2}{\frac{Se}{Si}.\frac{\alpha}{R\alpha / Ri} + \lambda.\frac{h_{eq}}{Ri}} \tag{5}$$

$$where \begin{cases} h_{eq} = \dfrac{S_{totale}}{2\pi.\sqrt{Rc/Ri}} \\ \alpha = 1 - \left(0.54 - \dfrac{0.153}{S_e / S_i}\right).\left(\dfrac{b}{Rc}\right)^{1/3} \\ \lambda = 0.05 + \dfrac{287.4}{\mathrm{Re}_w} \\ \mathrm{Re}_w = \dfrac{Dc.\rho}{\mu}.\dfrac{\dot{V}_0}{a.b.\left(0.089 - 0.204\dfrac{b}{Rc}\right)} \end{cases}$$

α is a correction factor for contraction, expressed as a function of the inlet geometry (the equation presented shows the case of a rectangular tangential inlet) and λ a friction factor either equals at 0.02 or a function of the inlet geometry and the inlet flow rate described by Muschelknautz.

The pressure drop is resolved into two terms. The first term ξ_i reflects the contribution by inlet losses and friction losses. The second term ξ_e results from the flow losses through the outlet pipe.

$$\Delta P = (\zeta e + \zeta i).\frac{\rho}{2}.w^2(Ri) \tag{6}$$

$$with \begin{cases} \zeta e = \dfrac{Ri}{Rc}.\left(\dfrac{1}{\left(1 - \dfrac{u(Ri).h_{eq}}{w(Ri).Ri}.\lambda\right)^2} - 1\right).\left(\dfrac{u(Ri)}{w(Ri)}\right)^2 \\ \zeta i = f.\left(2 + 3.\left(\dfrac{u(Ri)}{w(Ri)}\right)^{4/3} + \left(\dfrac{u(Ri)}{w(Ri)}\right)^2\right) \end{cases}$$

3.3. Leith and Licht model

This model [3,4] takes into account the temperature and provides the cut-diameter, the pressure drop and the efficiency of separation for a particle of diameter dp.
Leith and Licht describe particle motion in the entry and collection regions with the additional following assumptions:

- The tangential velocity of a particle is equal to the tangential velocity of the gas flow
- The tangential velocity is related to the radius by: $u.R^n$ = constant

A force balance and an equation on the particles collection yield to the equation 7:

$$\eta = 1 - \exp\left[-2.\left(\frac{G.\tau.\dot{V}_0}{D_c^3}.(n+1) \right)^{0.5/n+1} \right] \quad (7)$$

$$where \quad : \begin{cases} G = \dfrac{4.Dc.(2.Vs+V)}{a^2.b^2} \\ n = 1 - \left(1 - \dfrac{(12.Dc)^{0.14}}{2.5} \right).\left(\dfrac{T+460}{530} \right)^{0.3} \\ \tau = \dfrac{\rho_p.d_p^2}{18.\mu} \end{cases}$$

Note: G is a factor related to the configuration of the cyclone, n is related to the vortex and τ is the relaxation term.

The pressure drop is described by Equation 8:

$$\Delta P = 0.003.\rho.\left(\frac{16.\dot{V}_0^{\,2}}{a.b.Di^2} \right) \quad (8)$$

The cut-size is given by Equation 9:

$$d_p = \sqrt{\frac{9.\mu.Dc.a.b}{4\pi.Nt.\dot{V}_0.(\rho_p - \rho)}} \quad (9)$$

$$where \quad Nt = \frac{\dot{V}_{0:}}{ab} * \left(0.1079 - 0.00077.\frac{\dot{V}_0}{ab} + 1.924.10^{-6}.\left(\frac{\dot{V}_0}{ab} \right)^2 \right)$$

Nt is the number of tours done by the gas in the cyclone and is a function of the flowrate and the inlet geometry.

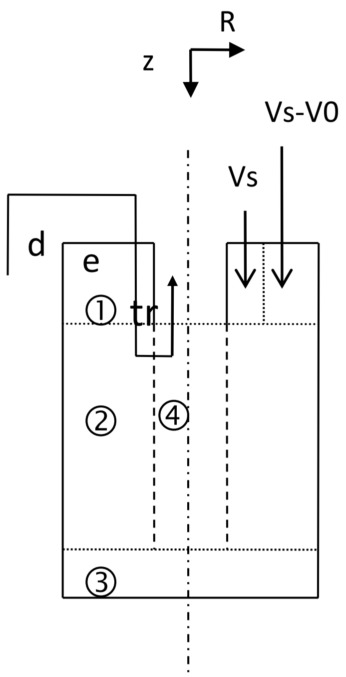
3.4. Lorenz model

This model [8] based on the four hypothesis below, takes into account the temperature and provides the cut-diameter, the pressure drop and the efficiency of separation for a particle of diameter dp.

Hypotheses:

- The tangential velocity depends only on the coordinate R and not on the axial coordinate (z).
- The particle move is determined as the sum of a aleatory movement (due to the gas) and a collective movement (due to the flow of particles).
- For the removal of particles from the gas, the particles must be prevented from entering the upward of flow into the exit and must be made to deposit on the wall of the cyclone during their residence time.
- Re-entrainment of already deposited particles from the conic part is essentially due to the increasing turbulent back-mixing of particles on the cyclone bottom.

The model is based on calculations made on the cyclone subdivided into five parts:



Region d, e, tr : Regions of the boundary layer flow
Region 1 : Entrance region
Region 2 : Region of downstream flow
Region 3 : Region of re-entrainment
Region 4 : Region of upstream flow

Figure 17 : Cyclone geometry used in calculations of Lorenz

The principle of the model is to form a differential system with mass balances in each regions. The equations of the system are functions of the geometry, the inlet flow rate and the two main parameters:

- $j_i(z)$: particle flux at the height z and in the region i
- $c_i(z)$: concentration of particles at the height z and in the region i

Before describing the system, several expressions have to be detail.

3.4.9. Parameters used in the system

⇒ **Equivalent cyclone**

For the commodity of the calculation, Lorenz defines an equivalent cyclone of same height H and of radius Rc*.

$$Rc^* = \sqrt{\frac{V_{cyclone}}{\pi.H}} \tag{10}$$

⇒ **The secondary flow**

The secondary flow is in the boundary layer along the cover plate and the outside of the vortex. This flow has to be considered because the boundary layer carries particles, which can reach the cyclone outlet without entering into the separation zone. Lorenz calculates it using equations from Ebert where n is the vortex exponent, δ_d the absolute boundary layer thickness and ϕ is a shape factor for the flow profile of the boundary layer.

$$\dot{V}s = 2.\pi.Rc.u(Rc).\left(\frac{Ri^*}{Rc}\right)^{1-n}.\delta(Ri^*).(0.26 - 0.154.\Phi) \tag{11}$$

$$with: \quad \begin{cases} \delta_d = f\left(R/_{Rc}, Re\right) \\ n = \dfrac{\ln\left(u(R)/u(Rc)\right)}{\ln(Rc/Ri)} \\ \Phi = -0.1 \\ Ri^* = Ri + 0.053.Rc \end{cases}$$

Ri* is the equivalent radius of the engagement length of cyclone. It is the sum of the real radius Ri and the thickness of the boundary layer of the tube.

⇒ **The tangential velocity**

The tangential velocities at R is calculated with the equations derived by Meissner[8]

$$u(R) = \frac{u(Rc)}{\frac{R}{Rc}.\left(1 + D.\left(1 - \frac{R}{Rc}\right)\right)} \tag{12}$$

$$with \quad D = \frac{u(Rc)}{w(Rc)}\left(\lambda_{cyl} + \frac{\lambda_{cone}}{\sin\varepsilon}\right)$$

In this equation, D is the angular momentum that characterizes the exchange of angular momentum between the wall and the gas. D is a function of the velocities u(Rc), w(Rc) and of λ_i: friction coefficients (λ_{cyl}, ,λ_{cone}). All the λ_i are considered constant. Usually this coefficient was considered equals to 0.007. Lorenz improved the previous models by using the following formula:

$$\lambda = \lambda_0.(1+2\sqrt{\phi_e}) \tag{13}$$

$$where \quad \begin{cases} \lambda_0 = 0.005 + \dfrac{287.4}{Re_w} \\ Re_w = \dfrac{u'(Rc).Dc.\rho}{\mu} \\ u'(Rc) = \dfrac{\dot{V}_0}{a.b.\left(0.889 - 0.204.\dfrac{b}{Rc}\right)} \\ \phi_e : inlet\ ch\arg e(kg/kg) \end{cases}$$

⇒ **Diffusivity due to turbulence**

In the case of radial exchange of particles, the model needs to take into account the diffusivity by the coefficient: D_{turb} given by equation (13):

$$D_{turb} = 0.006.\left(1+\arctan\left[\frac{Re_{tr}}{136864}\right]\right) \tag{14}$$

⇒ **Sedimentation velocity**

$$w_s(R) = \frac{(\rho_p - \rho).dp^2.u^2(R)}{18.\mu.R} \tag{15}$$

⇒ **Radial velocities**

$$w(Rc) = \frac{\dot{V}_0}{\pi.Rc^2} \tag{16}$$

$$w(Ri) = \frac{(\dot{V} - \dot{V}s)}{2\pi.Ri.(H-L)} \tag{17}$$

⇒ **Re-entrainment of particles**

The re-entrainment of particles already separated in the lower part is taken into account. The highest possible re-entrained mass flow is defined by the equation below:

$$\dot{m}_w = \dot{m}_{w,\max}.w(Re_s) \tag{18}$$

$$with: \quad \begin{cases} \dot{m}_{w,\max} = \dot{V}_0.c_0 - \dot{V}(L).c_4(L) - \dot{V}_s.c_{tr}(L) \\ w(Re_s) = 0.375 - 0.238\arctan\left(\dfrac{Re_s - 35776}{10548}\right) \end{cases}$$

⇒ **Flow rate at z**

$$\begin{cases} \dot{V}(z) = 0 & for : 0 \le z \le L \\ \dot{V}(z) = \left(\dot{V}_0 - \dot{V}_s\right) \cdot \dfrac{(H-z)}{(H-L)} & for : L \le z \le H \end{cases} \tag{19}$$

3.4.10. Equations of the differential system

The system of differential equations is obtained with mass balances in each region, by calculating the particle concentration on the axial co-ordinate z. The system is solved using transition conditions:

$$j_e(Rc^*) = w_s(Rc^*).c_e(z) \tag{20}$$

$$j_{tr}(Ri^*) = w_s(Ri^*).c_{tr}(z) \tag{21}$$

$\Rightarrow$ **Region e**

$$\frac{d}{dz}\left[(\dot{V}_0 - \dot{V}s).c_e(z)\right] = -2\pi.Rc^*.j_e(Rc^*) \tag{22}$$

$\Rightarrow$ **Region d**

$$\frac{d}{dz}\left[(\dot{V}_s.c_d(z)\right] = 2\pi.Rc^*.j_e(Rc^*) \tag{23}$$

$\Rightarrow$ **Region tr**

$$\frac{d}{dz}\left[(\dot{V}_s.c_{tr}(z)\right] = -2\pi.Ri^*.j_{tr}(Ri^*) \tag{24}$$

$\Rightarrow$ **Region ①**

$$\frac{d}{dz}\left[(\dot{V}_0 - \dot{V}s).c_1(z)\right] = -2\pi.Rc^*.j_1(Rc^*) + 2\pi.Ri^*.j_{tr}(Ri^*) \tag{25}$$

$with \quad j_1(Rc^*) = w_s(Rc^*).c_1(z)$

$\Rightarrow$ **Region ②**

$$\frac{d}{dz}\left[(\dot{V}(z).c_2(z)\right] = -2\pi.Rc^*.j_2(Rc^*) + 2\pi.Ri.j_{24}(Ri) \tag{26}$$

$$with \quad \begin{cases} j_2(Rc^*) = w_s(Rc^*).c_2(z) \\ j_{24}(Ri) = -D_{turb}.\dfrac{c_2(z) - c_2(z)}{(Rc^* - Ri)} + \left(w_s(Ri) - w_r(Ri)\right).c_4(z) & si \quad w_s(Ri) \ge w_r(Ri)(Ri) \\ j_{24}(Ri) = -D_{turb}.\dfrac{c_2(z) - c_2(z)}{(Rc^* - Ri)} + \left(w_s(Ri) - w_r(Ri)\right).c_2(z) & si \quad w_s(Ri) \le w_r \end{cases}$$

⇒ **Region ③**

$$j_2(z=1).\pi.(Rc*^2 - Ri^2) - j_4(z=1).\pi.Ri^2 - j_3(Rc*).2.\pi.Rc*^2.(H-1) = 0 \qquad (27)$$

$$with \quad \begin{cases} j_2(z=1) = \dfrac{\dot{V}(z=1).c_2(1)}{\pi.(Rc*^2 - Ri^2)} \\ j_4(z=1) = \dfrac{\dot{V}(z=1).c_4(1)}{\pi.Ri^2} \\ j_3(Rc*) = w_s(Rc*).c_{"} - \dfrac{\dot{m}_w}{2\pi.Rc*.(H-1)} \end{cases}$$

⇒ **Region④**

$$\frac{d}{dz}\left[(\dot{V}(z).c_4(z)\right] = -2\pi.Ri.j_{24}(Ri) \qquad (28)$$

3.4.11. Calculations of the parameters

⇒ **Efficiency**

$$\eta = 1 - \frac{\dfrac{\dot{V}_s}{\dot{V}_0}.c_{tr}(L) + \dfrac{\dot{V}_0 - \dot{V}_s}{\dot{V}_0}.c_4(L)}{c_0} \qquad (29)$$

⇒ **Pressure drop**

$$\Delta P = \xi.\frac{\rho}{2}.w^2(Rc) \qquad (30)$$

$$with \quad \begin{cases} \xi = \xi_e + \xi_{stat} + \xi_{dyn} + \xi_i \\ \xi_e = \left(\dfrac{u'(Rc)}{w(Rc)}\right)^2 - \left(\dfrac{u(Rc)}{w(Rc)}\right)^2 \\ \xi_{stat} = \left(\dfrac{u(Rc)}{w(Rc)}\right)^2.\dfrac{2}{(1+D)^4}.\left[\dfrac{1}{2.R^4.U^2} + \dfrac{3.D}{R^2U} - 3D.\ln(R^2U) - D^3R^2U - 3D - 0.5 + D^3\right] \\ \xi_{dyn} = \left(\dfrac{u(Rc)}{w(Rc)}\right)^2.(1-U^2) \\ \xi_i = 0.74.\left[2 + 3.\left(\dfrac{u(Ri)}{w(Ri)}\right)^{4/3} + \left(\dfrac{u(Ri)}{w(Ri)}\right)^2\right].\left(\dfrac{Rc}{Ri}\right)^4 \end{cases}$$

U and R are dimensionless terms:

$$U = \frac{u(Ri)}{u(Rc)}, \quad R = \frac{Ri}{Rc} \tag{31}$$

To take into account the effect of the solids loading, some modifications have been applied to the Lorenz model, which gives the best results at low solids loading. These modifications can be descript as follows:
The first modification is applied on the friction coefficient:

$$\lambda = \lambda_0 + 0.25\sqrt{\eta_{tot}\mu_e \frac{\rho_G}{\rho_S(1-\varepsilon)}}\left(\frac{D_C}{D_i}\right)^{-\frac{5}{8}} \tag{32}$$

In fact, at high solids loading, the wall is covered by a layer of particles which increases the frictions at the wall. The friction factor increases with the concentration of particles.

The second modification concern the inlet velocity. When the gas enters into the cyclone at velocity u_e, it is forced towards the wall by the pressure field of the vortex. The flow contracts so the velocity increases from u_e to u_a. This effect is represented by the contraction coefficient $\alpha = \frac{u_e r_e}{u_a R_c}(<1)$
this coefficient depends on the relative width $\beta = b/R_C$ and on the loading ratio μ_e. It can be calculated by:

$$\alpha = \frac{1}{\beta}\left[1-\sqrt{1+4\left[\left(\frac{\beta}{2}\right)^2 - \frac{\beta}{2}\right]\left[1-\frac{\beta(2-\beta)(1-\beta^2)}{(1+\mu_e)}\right]^{0.5}}\right] \tag{33}$$

The last correction concern the calculation of the total efficiency. In order to represent the particles which slit on the wall and are directly collected at the bottom of the cyclone, the critical loading theory could be used. Therefore the total efficiency is computed by:

$$\eta_{tot} = \left(1-\frac{\mu_G}{\mu_e}\right) + \frac{\mu_G}{\mu_e}\eta_i \tag{34}$$

where η_i is the efficiency calculated by the model
μ_G is the critical loading ratio which could be calculated by

$$\mu_G = 0.025\left(\frac{d^*}{d_{50}}\right)(10\mu_e)^k \tag{35}$$

if $\mu_e < 0.1$ then $k = -0.11 - 0.10\ln(\mu_e)$
$\mu_e > 0.1$ then $k = 0.15$
It results that the calculated total efficiency is constant while $\mu_e < \mu_G$, but increases quickly as soon as $\mu_e > \mu_G$ and until the maximum value of 1.0.

3.5. Mothes and Löffler model

As Lorenz model, this model enables to obtain the cut-diameter, the pressure drop and the efficiency of separation for a particle of diameter dp. Mothes and Löffler [5] established a

model on the principle described previously in Lorenz model. They were the first to propose a model based on a differential system of equations by separating the cyclone into four parts. Indeed Mothes model, as the first model of this type was made considering the following hypothesis which simplify the system:

- λ and D_{turb} are supposed constant

$\Rightarrow$ $\lambda = 0.007$

$\Rightarrow$ $D_{turb} = 0.0125$

- There is no re-entrainment

$\Rightarrow$ $m^{\&}_{w} = 0$

- Mothes considers that there is no separation in the region 1 above a/2 which implies that there is no regions d, e and tr

  $\Rightarrow$ No secondary flow (Vs = 0)

Hence it is easy to obtain the system of equations considering the simplifications above. For not weighing down the manual, the system in this case will not be written again. However, equations to modify are presented below:

- Identical equations: (9), (11), (14), (15), (25)$\rightarrow$(30)
- Equations to delete: (10), (17), (21) $\rightarrow$ (23)
- Modifications of Equations:

(12) : $\lambda = 0.007$

(13) : $D_{turb} = 0.0125$

(16), (18) $\rightarrow$ (20) : Vs = 0

(24) : Vs = 0 and deleting the term Ri*

Then the resolution of the system is the same considering the presented modifications.

3.6. Muschelknautz model

In the first version of the software, comparison between published measurements and model predictions, done by the Cyclone software, showed that the models used in the software predict pretty well the experimental results (obtained in a large range of operating conditions). However this agreement has been established only for relatively low solids loading (<10 $g.m^{-3}$). In fact, none of the four models as previously described takes the solids loading effect into account.

Based on these considerations, a new model was developed to take into account the effects of solids loading. Two types of modifications have been made. The first one is the application of the model developed by Muschelknautz. The second one is the modification of the Lorenz model with Muschelknautz [9,10,11,12,13,14] propositions on one hand and with Smolik empirical corrections [15] on the other hand.

In the Muschelknautz model, solids concentration *C* is replaced by the loading ratio μ_e, which is defined as a solids-to-fluid mass flow ratio:

$$\mu_e = \frac{\dot{M}_S}{\dot{M}_G} \tag{32}$$

where $\dot{M}_S$ is the solid flow rate, and $\dot{M}_G$ is the gas flow rate.
This ratio could be calculated from the concentration *C* by:

$$\mu_e = \frac{C\dot{V}_0}{\rho_G \dot{V}_0 \left(1 - \frac{C}{\rho_S}\right)} \tag{33}$$

where $\dot{V}_0$ is the inlet volumetric flow rate, ρ_S and ρ_G are the solids and the gas densities respectively.

The equations presented here have been established for a conventional slot-style inlet.
First the wall velocity $u(R_C)$ is computed by:

$$u(R_C) = \frac{u_e}{\alpha} \frac{r_e}{R_C} \tag{34}$$

where u_e is the inlet velocity $u_e = \frac{\dot{V}_0}{ab}$ and $r_e = R_C - \frac{b}{2}$ is the mean inlet radius. R_C is the cyclone radius, *a* and *b* are the height and the width of the cyclone inlet respectively. α is the entrance contraction coefficient which can be defined as:

$$\alpha = \frac{1}{\beta}\left[1 - \sqrt{1 + 4\left[\left(\frac{\beta}{2}\right)^2 - \frac{\beta}{2}\right]\left[1 - \frac{\beta(2-\beta)(1-\beta^2)}{(1+\mu_e)}\right]^{0.5}}\right] \tag{35}$$

with $\beta = b/R_C$

In order to compute the internal tangential velocity $u(r)$, the value of the total wall friction factor λ is necessary. At high solids loading, the wall is covered by a layer of particles which increases the frictions at the wall. In this way, Muschelknautz and Brunner [9] have shown that λ increase with the loading ratio μ_e, but also the total efficiency of the cyclone η_{tot} and the mean size particles d_{50} (represented by Froude number *Fr*):

$$\lambda = \lambda_0 + 0.25\sqrt{\eta_{tot}\mu_e Fr \frac{\rho_G}{\rho_S(1-\varepsilon)}}\left(\frac{D_C}{D_i}\right)^{-5/8} \tag{36}$$

where λ_0 is the friction coefficient factor between the gas and cyclone walls, ε is the porosity of solid particles (taken equal to 0.6), ρ_G and ρ_S are gas and solid densities, D_C and D_i are the cyclone and the vortex tube diameters.

Then the internal tangential velocity $u(r)$ at the radius *r* could be computed by:

$$u(r)=\frac{u(R_C)\frac{R_C}{r}}{1+\lambda\frac{S_{tot}u(R_C)}{2\dot{V}_0}\sqrt{\frac{R_C}{r}}} \tag{37}$$

with S_{tot} is the total intern surface of the cyclone.

Tangential velocity at vortex finder radius R_i allows cut size calculation:

$$d^*=\sqrt{\frac{18\eta(0.9\dot{V}_0)}{2\pi(\rho_S-\rho_G)u(R_i)^2(H-L)}} \qquad \text{if } \mathrm{Re}_p=\frac{\rho w_{S,50}d^*}{\mu}\le 0.5 \tag{38}$$

$$d^*=5.18\frac{\mu^{0.375}\rho_G{}^{0.25}w_{S,50}{}^{0.875}}{\left[\frac{(\rho_S-\rho_G)u(R_i)^2}{R_i}\right]^{0.625}} \qquad \text{if } \mathrm{Re}_p>0.5 \tag{39}$$

where $w_{S,50}$ is the settling velocity of a cut sized particle rotating at radius R_i:

$w_{S,50}=\frac{\dot{V}_0}{2\pi R_i H'}$ with H' the height of the cyclone at radius R_i.

At higher solid loading, the particles concentration makes an increase of the efficiency: the part of particles, which forms the layer on the wall, directly slips to the bottom of the cyclone, like a saltation. The other part of particles, which hold in turbulent suspension, is normally separated by the cyclone.

Muschelknautz introduced the critical load theory which describes the above effects. Considering the critical loading ratio μ_G, the separation efficiency consists in two different parts:

- the fraction of solids which exceeds μ_G : $\begin{cases}\mu_e-\mu_G & \text{if } \mu_e>\mu_G\\ 0 & \text{otherwise}\end{cases}$ is directly collected at the bottom of the cyclone without classification and separation
- the remaining fraction which is limited by μ_G : $\begin{cases}\mu_G & \text{if } \mu_e>\mu_G\\ \mu_e & \text{otherwise}\end{cases}$ holds in suspension and is separated in the vortex cyclone with the above efficiency η_i

So at high solids loading, if $\mu_e > \mu_G$, *the total efficiency may be calculated as:*

$$\eta_{tot}=\left(1-\frac{\mu_G}{\mu_e}\right)+\frac{\mu_G}{\mu_e}\eta_i \tag{40}$$

According to Muschelknautz, the critical loading ratio depends on the solid size of the feed d_{50}, the cut size d^* and also the loading ratio itself. These equations could be used:

$$\mu_G=0.025\left(\frac{d^*}{d_{50}}\right)(10\mu_e)^k \tag{41}$$

if $\mu_e < 0.1$ $\quad$ *k=-0.11-0.10ln(*μ_e*)*

if $\mu_e > 0.1$ $k=0.15$

Finally, the pressure drop is the sum of two terms. In fact, according to Muschelknautz, pressure loss across cyclone occurs, primarily, as a result of friction with walls and Losses in cyclone body:

$$\Delta P_e = \lambda \frac{S_{tot}}{0.9\dot{V}_0} \frac{\rho_G}{2} \left(u(R_i)u(R_C)\right)^{1.5} \tag{42}$$

Losses in the vortex tube finder:

$$\Delta P_i = \left[2 + 3\left(\frac{u(R_i)}{w(R_i)}\right)^{4/3} + \left(\frac{u(R_i)}{w(R_i)}\right)^2\right] \frac{\rho_G}{2} \left(w(R_i)\right)^2 \tag{43}$$

Thus the total pressure drop is the sum:

$$\Delta P = \Delta P_e + \Delta P_i \tag{44}$$

4. Studies of literature cases

In order to verify the validity of the software, literature's reports were studied to compare experimental values to theoretical values obtained with the program. Nine articles were found and works done on it [12, 13, 14, 15, 16, 17, 18, 20, 21].

This study leads to conclusions that may help to choose the best model in function of the operating conditions. The conclusions are summarized in the following tables.

General conclusions are presented in term of accuracy of models for different experimental conclusions. Percentage values are of course approximate because of the high difficulty to take into account all the parameters, but they give a good idea of which model may be the more appropriate.

T = 293 K

		Inlet flow rate < 10m/s	Inlet flow rate > 10m/s
Collection efficiency		**Lorenz (error ~ 20%)** Mothes (error ~ 30%) Leicht & Licht (error ~ 85%)	**Lorenz (error ~ 1%)** **Mothes (error ~ 1%)** Leicht & Licht (error ~ 15%)
Separation efficiency		**Lorenz (error ~ 14%)** **Mothes (error ~ 12%)** Leicht & Licht (error ~ 17%)	**Lorenz (error ~ 1%)** **Mothes (error ~ 2%)** **Leicht & Licht (error ~ 5%)**
Cut-size		Lorenz (error ~ 47%) Mothes (error ~ 41%) **Leicht & Licht (error ~ 32%)** Barth (error ~ 67%)	**Lorenz (error ~ 14%)** **Mothes (error ~ 16%)** Leicht & Licht (error ~ 52%) Barth (error ~ 25%)
Pressure drop	Geometry: Type Stairmand	Lorenz (error ~ 48%) Mothes (error ~ 74%) Leicht & Licht (error ~ 84%) **Barth (error ~ 19%)**	**Lorenz (error ~ 16%)** **Mothes (error ~ 16%)** Leicht & Licht (error ~ 20%) Barth (error ~ 30%)
	Geometry: Type ≠ Stairmand	Lorenz (error ~ 214%) Mothes (error ~ 321%) Leicht & Licht (error ~ 233%) **Barth (error ~ 147%)**	Lorenz (error ~ 127%) Mothes (error ~ 158%) Leicht & Licht (error ~ 105%) **Barth (error ~ 36%)**

*Table 20- **Comparison of models predictions at different flow rate at room temperature.***

High temperature

	293K < T < 900K		T > 900 K
	Pressure < 2 bar	**Pressure > 2 bar**	
Collection efficiency			Lorenz (error ~ 26%) **Mothes (error ~ 11%)** **Leicht & Licht (error ~ 9%)**
Separation efficiency	**Lorenz (error ~ 9%)** Mothes (error ~ 70%) Leicht & Licht (error ~ 80%)	**Lorenz (error ~ 11%)** Mothes (error ~ 40%) Leicht & Licht (error ~ 60%)	
Cut-size	**Lorenz (error ~ 12%)** Mothes (error ~ 45%) **Leicht & Licht (error ~ 12%)** **Barth (error ~ 16%)**	**Lorenz (error ~ 8%)** Mothes (error ~ 42%) Leicht & Licht (error ~ 80%) **Barth (error ~ 9%)**	Lorenz (error ~ 187%) Mothes (error ~ 96%) **Leicht & Licht (error ~ 47%)** Barth (error ~ 511%)
Pressure drop	**Lorenz (error ~ 45%)** Mothes (error ~ 235%) Leicht & Licht (error ~ 236%) Barth (error ~ 72%)	**Lorenz (error ~ 55%)** Mothes (error ~ 241%) Leicht & Licht (error ~ 241%) Barth (error ~ 77%)	**Lorenz (error ~ 88%)** **Mothes (error ~ 80%)** **Leicht & Licht (error ~ 81%)** Barth (error ~ 90%)

*Table 21- **Comparison of models predictions at different pressure and high temperature.***

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